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Arch-Free flow in aerated silo discharge of cohesive powders

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ABSTRACT

Arching can occur during silo discharge of cohesive powders. In general this happens when the outlet size is not wide enough. Flow aid devices, such as aeration pads, are commonly used in the industry to achieve proper flow of cohesive materials. However, no design criteria are presently available for such kind of devices and, in particular, for the intensity of aeration to be used to avoid arching. Aim of this paper is the evaluation of the limiting aeration condition to produce the collapse of established arches and the minimum aeration rate necessary for no arching discharge flow. Experimental tests are carried out in an aerated flat bottom silo. The measured quantities are the aeration rate at arch collapse and the arch size. Powder permeability is characterized by fluidization experiments. A simplified model is proposed to assess on the prevailing physical phenomena and predictively evaluate the minimum aeration rate to determine no arching discharge flow.

1. Introduction

Fine and cohesive powders may discharge with some difficulty from silos and hoppers due to the presence of both gas–solid fluid dynamic and solid–solid cohesive interactions. Gas–solid fluid dynamic interactions, in fact, can generate gas pressure gradients opposed to the solids flow [1]. Solid–solid cohesive interactions, enhanced by consolidation phenomena, can determine the formation of stable structures, such as pipes and arches (domes) which may stop the solids flow. Aeration of powders during silo discharge is used to overcome both these problems. The main effect of aeration is to achieve favourable pressure gradients near the hopper outlet. In the prediction of the discharge rate of fine aeratable powders (group A according to Geldart [2], and Geldart and Williams [3]) this effect can be simply accounted for by including the local gas pressure gradient in the effective field of mass forces [4,5]. A similar approach can be followed also for cohesive powders (group C according to [3]) if the aggregative behaviour of these powders is properly considered [6]. It has also been proven that aeration cannot modify the solid flow properties but affects only the resulting stress state [7–9]. Therefore, it can be hypothesized that the breakage of arches due to aeration can be approached with the conventional analysis on arch stability, in which an arch of consolidated powder is considered stable when its strength is high enough to sustain the stresses determined by its weight. In particular, the gas pressure gradient can be included in the analysis as an additional mass force acting for the arch consolidation and breakage.

Drescher [10] classified the models developed to predict arch stability into two different categories according to the physical approach followed. In "structural mechanics" models, the arch or dome is regarded as a structural element loaded by its own weight. In "continuum mechanics" models the formation of stable arches is identified with the static equilibrium of the whole mass of material in the hopper with the arch completely developed, that is without the contribution of any stress supporting the mass from below [11]. Several authors [12–15] developed models according to the first of these two categories. In particular the approach due to Jenike [14] will be followed in this paper. According to it, when the arch is on the verge of collapsing, its weight is just balanced by the vertical component of the maximum normal stress close to the walls as it is shown in Fig. 1a). Jenike and Leser [16] derived the condition to determine the smallest outlet diameter, D, from the force balance by assuming the following condition for arch failure:

$$\sigma_1' = \frac{\gamma D}{H(\theta)} \geq \sigma_c \tag{1}$$

where σ_1' is the abutment stress of the arch, σ_c is the unconfined yield strength of the powder in use, γ is the mass force/unit volume and $H(\theta)$ is a function which takes into account the effects of variation of the thickness of the arch with the silo geometry and the hopper half angle θ. Under gravity flow:

$$\gamma = \rho_b g \tag{2}$$

where ρ_b is the powder bulk density and g the acceleration due to gravity. Jenike and Leser [16] reported a graphical solution of $H(\theta)$ that is well approximated by the following equation [13]:

$$\frac{1}{H(\theta)} = \left(\frac{65}{130+\theta}\right)^i \left(\frac{200}{200+\theta}\right)^{1-i} \tag{3}$$

where the silo geometry is accounted for by the exponent i, $i=0$ for wedge hoppers and $i=1$ for conical hoppers. More recently, an alternative

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description of the shape of a cohesive arch in hoppers and silo was proposed by Matchett [17].

In mass flow silos, the consolidation stress at the outlet, σ_1, depends on the distance from the hypothetical hopper vertex. According to Jenike [14], it is possible to show that:

$$\sigma_1 = \gamma D \frac{(1+\sin\phi_e)\ s\ (m, \theta, \phi_e, \phi_w)}{2\ \sin\theta} \quad (4)$$

where s is a complex function depending on the hopper geometry (wedge or conical) on its half angle, θ, on the tensional state ($m=1$ for active state, $m=-1$ for passive state), on the powder effective angle of internal friction, ϕ_e, and on the powder angle of wall friction, ϕ_w. Combining Eqs. (1) and (4) it is possible to obtain the relationship between $\sigma_1{}'$ and σ_1 in terms of their ratio, the flow factor *ff*:

$$ff = \frac{\sigma_1}{\sigma_1'} = H(\theta) \frac{(1+\sin\phi_e)\, s(m, \theta, \phi_e, \phi_w)}{2\ \sin\theta} \quad (5)$$

Diagrams reporting the no arching flow factors for conical and wedge hoppers are given by Jenike [18] for different values of θ, ϕ_e and ϕ_w. In funnel flow bins, the powder forms its own flow channel. In this case Jenike [18] recommended that the technique proposed for mass flow may be adapted with the assumption that

$$\phi_w = \arctan[\sin(\phi_e)]. \quad (6)$$

With such an assumption the flow factor *ff* becomes a function of ϕ_e and of the slope angle of the live channel, θ'. *ff* contours for arching in funnel flow are reported in Jenike ([18], p.187). The flow factor *ff* can be compared with the powder flow function *FF* in which the unconfined yield strength σ_c is given as a function of the consolidation stress σ_1:

$$\sigma_c = FF(\sigma_1) \quad (7)$$

An example of the graphical construction connected to this procedure is reported in the following in Fig. 4. An arch characterized by its diameter D is stable if the limiting yield stress σ_1/ff, obtained with Eq. (4), is smaller than the unconfined yield strength $FF(\sigma_1)$ obtained with experimental measurement of the flow function. The whole hopper design procedure to prevent arching both in mass flow and funnel flow hoppers was recently reported by Schulze [19].

Kurz [20] suggested that, in order to describe the effective state of stress within an aerated powder, the gas pressure gradient together with gravity made up the effective body force γ^* promoting the arch collapse. This assumption implies that aeration does not change the powder flow properties which was actually demonstrated by more recent findings [7–9]. Kurz [20] calculated the extra abutment effect due to air flow by integrating the Darcy law with an analogue model. However, he found an under prediction of the aeration rate necessary to break the arch. Jochem and Schwedes [21] extended the analysis by Kurz [20] by calculating the gas pressure field inside the aerated hopper to derive the air flow rate required for the destruction of the arch.

In this paper we will demonstrate that this approach is correct if the effective body force is used not only to account for the extra forces acting on the arch collapse, but also to account for the extra consolidation of the material within the arch. We will also propose a design approach to evaluate the critical aeration rate necessary to avoid arching with a cohesive powder.

2. Theoretical background

According to Fig. 1b) the gas pressure gradient can be assumed to be on average coaxial to the gravity close to the outlet and, therefore, the effective body force can be assumed to be the sum of the weight and of the force due to the interstitial air pressure gradient:

$$\gamma^* \cong \rho_b g + \left.\frac{\partial p}{\partial r}\right|_d \quad (8)$$

where, ρ_b is the powder bulk density, g the acceleration due to gravity, p the gas pressure, r the distance to the ideal vertex of the conical domain interested by the solids flow, the subscript "d" to the derivative indicates that its relevant value has to be evaluated on the dome surface. Assuming that this extra force acts not only to determine the dome collapse represented, but also the consolidation state given, both Eqs. (1) and (4) will continue to apply with γ^* in place of γ and, therefore, the same flow factor given by Jenike Eq. (5) will still apply. This means that independently of the dome size, at a certain aeration rate the critical condition for the arch collapse in terms of consolidation stress σ_1 and material strength σ_c is the same of the non aerated case and can be calculated with the Jenike procedure in advance, simply by searching the intersection between the material flow function and the silo flow factor.

In order to better understand the effect of air flow rate on the arch collapse we have to express the gas pressure gradient as a function of the air flow rate. A reasonable estimate of the gas pressure gradient at the dome can be made as follows:

$$\left.\frac{\partial p}{\partial r}\right|_d = n\eta k U_d \quad (9)$$

Eq. (9) describes the pressure gradient (positive in the silo inward direction) as a function of the bed permeability, k, the local gas velocity, U_d (positive in the outward direction), the gas viscosity, η,

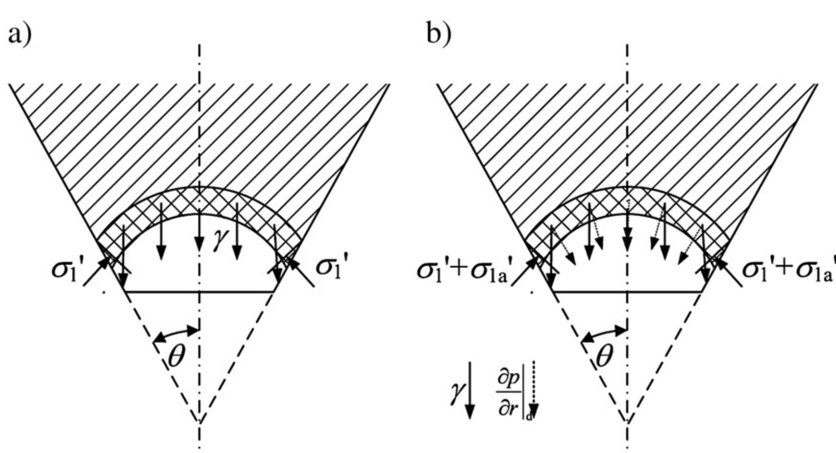

Fig. 1. Forces acting on a stable dome: a) non aerated case; b) aerated case.